TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FLIGHT TESTS OF AN AIRPLANE SHOWING DEPENDENCE OF THE MAXIMUM LIFT COEFFICIENT ON THE TEST CONDITIONS

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Washington
November 1937

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SUMMARY

Data are presented to show the extent to which the maximum lift coefficient and, consequently, the minimum speed of an airplane, as determined by flight tests, may vary with test conditions. The data show that $C_{L_{max}}$ may vary by as much as 14 percent, depending on the altitude and wing loading at which the tests are made, the position or motion of the propeller, and the rate at which the angle of attack is changing when the maximum lift coefficient is obtained. The variation of the maximum lift coefficient with these factors, which are under the control of the test engineer, shows the need of standardizing the test procedure. A further variation is shown with wing conditions as affected by weathering and vibration, factors that cannot be completely controlled.

INTRODUCTION

General experience with the measurement of minimum speeds and maximum lift coefficients has indicated considerable difficulty in obtaining agreement between successive measurements on a given airplane, between wind-tunnel and flight tests of a complete airplane, and between measured and predicted minimum speeds for a given airplane. The purpose of the present paper is to present N.A.C.A. flight experience with one airplane and to discuss the factors that were found to affect the minimum speeds and the maximum lift coefficients obtained under different test conditions. The factors investigated were Reynolds Number, which was varied by changing the wing loading and altitude, propeller condition, rate of change of angle of attack, and wing-surface condition. The data were obtained in connection with one phase of a general

investigation of scale effect, which included a comparison of results obtained in flight with those obtained in the full-scale wind tunnel.

APPARATUS AND METHOD

The Fairchild 22 airplane used in the investigation is a small two-place parasol monoplane powered with a 145-horsepower Warner engine and equipped with a specially finished wing of rectangular plan form and N.A.C.A. $2R_112$ section. The wing has semicircular tips and a slight trailing-edge cut-out at the center section (fig. 1). The mean chord, which was used as a reference length in the computation of Reynolds Numbers, is 5.21 feet.

In order to reduce the effects of surface roughness, the portion of the wing including the leading edge and extending on the upper surface 18 inches and on the lower surface 12 inches back from the leading edge was given a very smooth, uniform finish. The entire wing was polished and waxed at the beginning of the flight tests and the portion of the wing having the special finish was repolished before each flight. As a further aid in securing good flow conditions, the gap between the wing and the aileron was closed by means of a flexible fabric seal.

The recording instruments used in the investigation consisted of an air-speed meter, an angle-of-attack meter, an accelerometer, and a timer. The air-speed recorder was connected to a swiveling pitot-static head mounted on a light boom about one chord length forward of the leading edge of the right wing at the semispan and slightly below the plane of the chord. This air-speed recording system was calibrated in flight by the use of a suspended static head as described in reference 1.

The angle-of-attack recorder consisted of a differential-pressure-type yaw head mounted on a boom similar to that employed for the air-speed head but on the opposite side of the airplane. The installation of the booms is shown in figure 2. The angle-of-attack recorder was calibrated in steady glides with the aid of a recording inclinometer by timing the airplane for a known change of altitude as indicated by a calibrated Kollsman altimeter. The accelerometer was used to record the components of acceleration parallel to the X and Z body axes. The

timer was used in determining the rate of change of angle of attack and for synchronizing the records from the different instruments.

The general method employed in the investigation was to fly the airplane with a known wing loading at the desired altitude at which either a series of steady glides or a series of pull-ups to the stall at various rates of change of angle of attack would be made. The flights were made only when the air was smooth. The air speed, angle of attack, and accelerations were recorded by the instruments as functions of time. The approximate time at which the lift coefficient reached a maximum in each run was obtained from an inspection of the film records. The value of the lift coefficient was then calculated for several instants at intervals of 1 second or less in the vicinity of the time at which the maximum value was expected.

In the calculation of the lift coefficients the resultant force acting on the airplane and its direction relative to the airplane axes were computed from the accelerometer records and the weight of the airplane at the time of the tests. The lift L, which is defined as the component of force normal to the wind axis, was determined from the resultant force and the angle of attack. The weight for each flight was estimated from the weight of the airplane and pilot obtained immediately after the flight by correcting for the fuel used in returning to the hangar. The dynamic pressure q was obtained by correcting the pressure given by the air-speed head for the position error. From the simultaneous values of L and q so found, the lift coefficient was computed from the relation

$$C_L = \frac{L}{qS}$$

in which S is the area of the wing (171 square feet).

Variation of the Reynolds Number was secured by varying the wing loading and the altitude at which the tests were made. For the low Reynolds Number condition, the airplane was flown with the lightest load and at the highest practicable altitude. High Reynolds Numbers were obtained by flying with full service loading and 500 pounds of ballast in the front seat and at the lowest practicable altitude.

Tests were made with the propeller stopped in both vertical and horizontal positions, idling, and turning at full speed. The rate of change of the angle of attack was varied by changing the rate at which the control stick was moved during the pull-ups.

Although, as has been noted, the portion of the wing having a special finish was repolished before each flight, some small irregularities in the wing surface developed from time to time owing to checking of the dope finish, particularly at the leading-edge reinforcement. In order to obtain an indication of the effect of the small ridge thus formed, several flights were made in which a linen thread 6 feet long and having a diameter of approximately 0.015 inch was attached to the central portion of the upper surface of the smooth wing about 3 inches back of the leading edge.

RESULTS AND DISCUSSION

The results of the investigation are given in tabular form in tables I to V. Since minimum speed is dependent upon the loading of the airplane, as well as upon the lift coefficient, the results are given in most cases in terms of maximum lift coefficient rather than in terms of minimum speed. The corresponding percentage variations in the indicated minimum speed for a given loading are approximately half as large as those for maximum lift coefficient.

All of the values given in the tables, with the exception noted in table III, represent the mean obtained from four to six different runs made under supposedly identical conditions in one flight. The values for all the runs from each flight were averaged to increase the precision of the final results. Table I has been included to show the variation that occurred in the results of the individual runs of the different flights as an indication of the precision to be expected when measurements are made under constant test conditions. Data from two representative flights showing respectively the minimum and maximum variations in the results of individual runs for a series of 20 flights are presented. Calculations made on the basis of the results of this series of flights indicate a probable maximum variation in the values of $C_{L_{max}}$ of 2.5 percent and an average deviation of the individual results from the mean value of less than 1 percent.

The air speeds given in table I are those occurring at the instant the maximum lift coefficient was attained. It is important to note that the occurrence of the maximum lift coefficient and of the minimum recorded air speed were rarely coincident, the speed usually continuing to fall off slightly after the beginning of the stall. The results of a typical run showing this effect are given in figure 3 in which air speed, lift coefficient, and elevator deflection are plotted against time. As will be seen from the figure, following the attainment of the maximum lift coefficient, there is a short period during which the speed falls below the stalling speed before the increase normally associated with the stall is apparent. The minimum speed for the run shown is 0.8 of a mile per hour below that corresponding to the maximum lift coefficient. It is believed that the difference between the minimum and stalling speeds results from an inertia effect similar to that occurring in whip stalls and is dependent on the rate of change of angle of attack at the stall and on the stalling characteristics of the wing being tested.

The attainment of a speed lower than the stalling speed in gradual pull-ups of the type made is of practical importance only in regard to the possible errors it may introduce in the results when the accelerations are not recorded. If the air speed is recorded, it is believed that the stalling speed may be chosen without difficulty once the general character of the records is appreciated. If an indicating instead of a recording air-speed meter is used, the observer should be familiar with the expected sequence of events and should discount any sudden changes in the reading of the indicator as the airplane noses over or falls off on a wing following the stall; figure 3 shows such a change occurring after a time interval of 8 seconds.

In connection with the measurements, care should be taken to secure an accurate calibration of the air-speed recording installation, particularly in the speed range just above the stall. For example, even though a swiveling air-speed head was used in this investigation and was mounted approximately one chord length forward of the leading edge, considerable correction was necessary, as shown in figure 4, for one value of the wing loading. As will be noted, the error increases rapidly as the stalling speed is approached, showing that the extrapolation of a calibration curve which does not extend to the stalling speed may lead to serious errors.

Effect of rate of change of angle of attack.- The wind-tunnel tests with which flight measurements are generally compared are usually made with the model stationary and, for purposes of comparison, it would be desirable if flight tests could be made in the same manner. Comparable test conditions are very difficult to secure in flight, however, because of the unstable character of the atmosphere. Any disturbance is likely to precipitate a partial stall of the airplane and, even if the stall is only temporary in character, the records obtained for the subsequent complete stall will be influenced by the so-called "hysteresis" shown by the lift curve. Moreover, many airplanes cannot be flown steadily at the stall. In practice, the procedure is either to fly the airplane at the minimum steady speed or to increase slowly the angle of attack until the airplane stalls. These two methods are usually assumed to give comparable results. Actually, the difference is appreciable. Table II shows the difference in the results obtained for steady glides and for pull-ups made at the slowest possible rate at which the pilot could be sure that the increase of angle of attack was continuous. The rate of change in the angle of attack averaged about 0.2° per second, which corresponded to a speed decrease of the order of 0.5 mile per hour per second. As will be noted, the tests showed a difference of approximately 3 percent in $C_{L_{max}}$ for the two methods. Further tests were made in which the rate of pull-up was varied. The data from these tests are not given because it is impossible to obtain consistent variation in the speed of the pull-ups, but the results indicate that $C_{L_{max}}$ increases with the speed of the pull-up. These conclusions have been substantiated by unreported tests of the airplane in the full-scale tunnel and of the N.A.C.A. $2R_1 12$ airfoil alone. The airfoil tests indicate that the greatest increase in $C_{L_{max}}$ lies between $d\alpha/dt = 0$ and $d\alpha/dt = 0.2^{\circ}$ per second, the increase between $d\alpha/dt = 0.2^{\circ}$ and $d\alpha/dt = 0.4^{\circ}$ per second being only one-third as large.

Effect of propeller.- The variation in the maximum lift coefficient with the propeller condition is shown in table III. It will be noted that with the propeller stopped the lift coefficient depends to some extent upon the propeller position. The difference is usually not large and is probably within the precision of the average test, but the small consistent increase that results when the propeller is stopped in the horizontal position indi-

cates its presence. This effect is not of great importance, because it is usually obscured by factors over which the test engineer has no control. The effect of rotation of the propeller, however, is of importance. The data indicate that, for the airplane tested, $C_{L_{max}}$ is 4 percent greater for the propeller idling at about 550 r.p.m. than for the propeller stopped vertically. It is, of course, to be expected that even for the same airplane the difference will vary with the idling speed of the engine, as determined by the throttle stop setting. The effect of the propeller will also vary with the geometric arrangement of the airplane and the relation of the propeller to the wing. The large increase in $C_{L_{max}}$ obtained with full throttle, as shown in table III, is usually observed.

Effect of Reynolds Number.- It is generally understood that, in the application of model data to an airplane, allowance should be made for an increase of $C_{L_{max}}$ with Reynolds Number. It is not so widely appreciated, however, that the variation of Reynolds Number for different conditions that may be encountered during the course of a prolonged series of tests may be sufficient to prevent the attainment of consistent results. The variation of $C_{L_{max}}$ with Reynolds Number is shown in table IV. It is of interest to note that the increment is approximately the same for the two propeller conditions illustrated. As previously noted, the Reynolds Number was varied by flying with light loading at high altitude and with heavy loading at low altitude. The weight variation was from 1,625 to 2,232 pounds, or 37 percent of the gross weight for the lighter loading, which is somewhat larger than the pay load of most airplanes. In the present case the difference in weight accounted for about 84 percent of the change in Reynolds Number, the altitude difference having only a small effect. It should be noted, however, that even with no change in the loading a large variation in Reynolds Number may occur if tests are made at low altitude in winter and at high altitude in summer. For example, the variation in the Reynolds Number corresponding to a change from an altitude of 2,000 feet and a temperature of 0° F. to an altitude of 10,000 feet and a temperature of 50° F. is approximately 33 percent.

Effect of wing condition.- The wing used in the tests had been in storage for a considerable period prior to the beginning of the project. After the surface had been pre-

pared the wing was installed and the airplane rigged for the tests. After several preliminary flights the airplane was tested in the full-scale tunnel, tested in flight, retested in the tunnel, and finally retested again in flight. The time elapsing between the installation of the wing and the final test was 225 days. The data for a number of flights made under comparable conditions at intervals during this time show a small consistent decrease in $C_{L_{max}}$ with time. This decrease was particularly noticeable after the first series of tunnel tests, after which a drop of more than 5 percent was observed.

Observations showed some deterioration of the wing finish during the flight tests which could not have been prevented. The sag of the fabric between the ribs varied from day to day, probably with humidity and temperature, and the angle of the wing setting on one portion of the wing changed about 0.5° between the beginning and the completion of the tests. It is not believed that the results of any one of these changes by itself could cause differences in lift of the magnitude noted. No satisfactory explanation has been found for the large drop in the maximum lift coefficient observed after the first series of tunnel tests, but it is believed that the relatively severe vibration which occurred at the stall in the tunnel may have resulted in the immediate take-up of all initial slack in the wing rigging. This process would normally have taken a considerably longer period of time in flight. The decrease in $C_{L_{max}}$ caused by the small ridge secured by doping a linen thread to the upper surface of the wing, as previously explained, is shown by table V to be about 1.4 percent.

CONCLUDING REMARKS

Variations in the rate of change of angle of attack, the propeller condition, and the Reynolds Number are under the control of the test engineer. The summation of the deviations observed, due to variations in these test conditions for the same wing condition, amounted for this airplane to 14 percent, which illustrates the necessity of maintaining constant test conditions if consistent results are to be obtained. The desirability of standardizing the test procedure in measuring $C_{L_{max}}$ and minimum speed, so that the results of different tests will be to some extent

comparable, is clearly shown. Obviously the test conditions should always be specified in giving the value of $C_{L_{max}}$ or of the minimum speed of an airplane.

It may be stated that, for a series of tests made over a relatively short period of time, all of which are made at the same pressure altitude, with the propeller stopped in the same position, with the same wing loading, and with the angle of attack increasing to stall as slowly as the pilot can accomplish it by steady and continuous motion of the elevator, the maximum dispersion in the values of $C_{L_{max}}$ and of minimum speed is unlikely to exceed 3 percent and 1.5 percent, respectively, and the corresponding probable errors should not exceed one-third of these values.

The condition of the wing, as affected by weathering, weaving, or warping, and by changes in the rigging is only partly under the control of the test engineer. If considerable time elapses or if the wing is subjected to relatively severe strains between tests, it is possible, at least in the case of a wing of wood and fabric construction, that the results of the later test may show a decrease in $C_{L_{max}}$ of several percent of the value obtained when the wing was first installed.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 13, 1937.

REFERENCE

1. Thompson, F. L.: The Measurement of Air Speed of Airplanes. T.N. No. 616, N.A.C.A., 1937.

TABLE I

Variation of Results Obtained Under Similar Conditions

Run	Pressure (in. Hg)	Temperature (°F.)	Reynolds Number (millions)	Indicated air speed (m.p.h.)	$C_{L_{max}}$
Wing surface roughened by doping thread on wing					
1	20.675	45	2.195	53.0	1.293
2	20.675	45	2.215	53.3	1.299
3	20.675	45	2.198	53.2	1.301
4	20.675	45	2.198	53.3	1.299
Average	20.675	45	2.202	53.2	1.298

Maximum dispersion in $C_{L_{max}}$ = 0.008, or 0.6 percent

Run	Pressure (in. Hg)	Temperature (°F.)	Reynolds Number (millions)	Indicated air speed (m.p.h.)	$C_{L_{max}}$
Wing surface polished					
1	28.36	23.5	3.002	58.2	1.478
2	28.36	23.5	2.995	58.3	1.470
3	28.36	23.5	3.043	59.0	1.435
4	28.36	23.5	3.055	59.2	1.424
5	28.36	23.5	3.120	59.8	1.381
Average	28.36	23.5	3.040	58.9	1.438

Maximum dispersion in $C_{L_{max}}$ = 0.097, or 6.8 percent

TABLE II

Effect of Type of Maneuver on $C_{L_{max}}$

Maneuver	Propeller condition	Reynolds Number (millions)	$C_{L_{max}}$
Steady glides	Stopped vertically	2.207	1.290
Slow pull-ups	Stopped vertically	2.245	1.320
Steady glides	Stopped horizontally	2.258	1.311
Slow pull-ups	Stopped horizontally	2.200	1.366

TABLE III

Variation of $C_{L_{max}}$ with Propeller Condition

Propeller condition	Maneuver	Reynolds Number (millions)	$C_{L_{max}}$
Stopped vertically	Slow pull-ups	2.245	1.320
Stopped horizontally	Slow pull-ups	2.200	1.366
Stopped vertically	Slow pull-ups	2.840	1.456
Stopped horizontally	Slow pull-ups	2.716	1.468
Stopped vertically	Steady glides	2.207	1.290
Stopped horizontally	Steady glides	2.258	1.311
Stopped horizontally	Slow pull-ups	2.238	1.339
Idling*	Slow pull-ups	2.195	1.395
Full throttle	Slow pull-ups	1.957	1.732

*Only one run.

TABLE IV

Variation of $C_{L_{max}}$ with Reynolds Number

Reynolds Number (millions)	$C_{L_{max}}$	Propeller condition
2.260	1.325	Propeller vertical
3.020	1.467	Propeller vertical
2.200	1.366	Propeller horizontal
2.716	1.468	Propeller horizontal

TABLE V

Variation of $C_{L_{max}}$ with Wing Surface Condition

Wing surface condition	Reynolds Number (millions)	$C_{L_{max}}$
Highly polished	2.204	1.317
Thread on upper surface	2.202	1.298

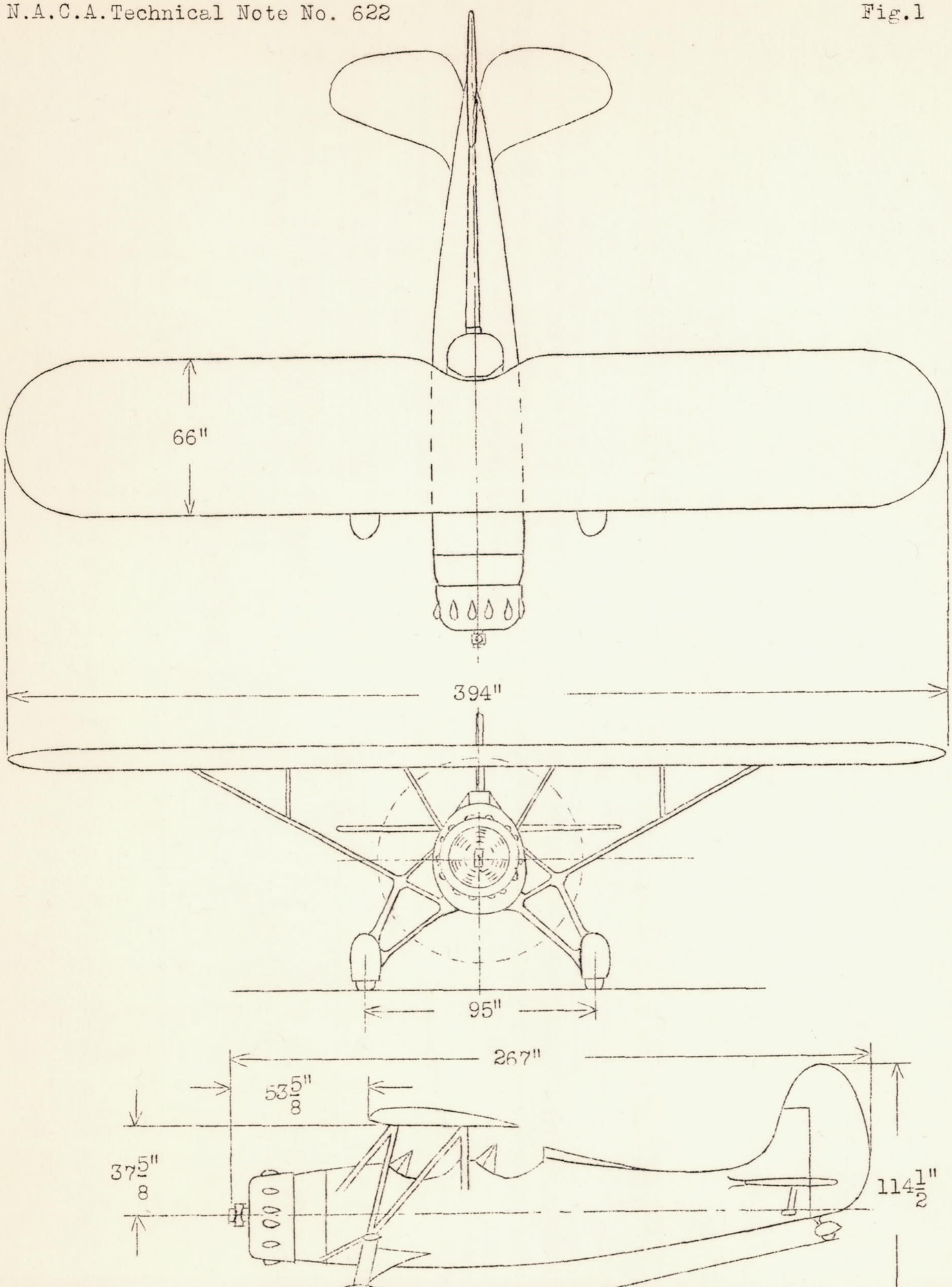

Figure 1.- Fairchild 22 Airplane.

Figure 2.- Three-quarter front view of Fairchild 22 airplane.

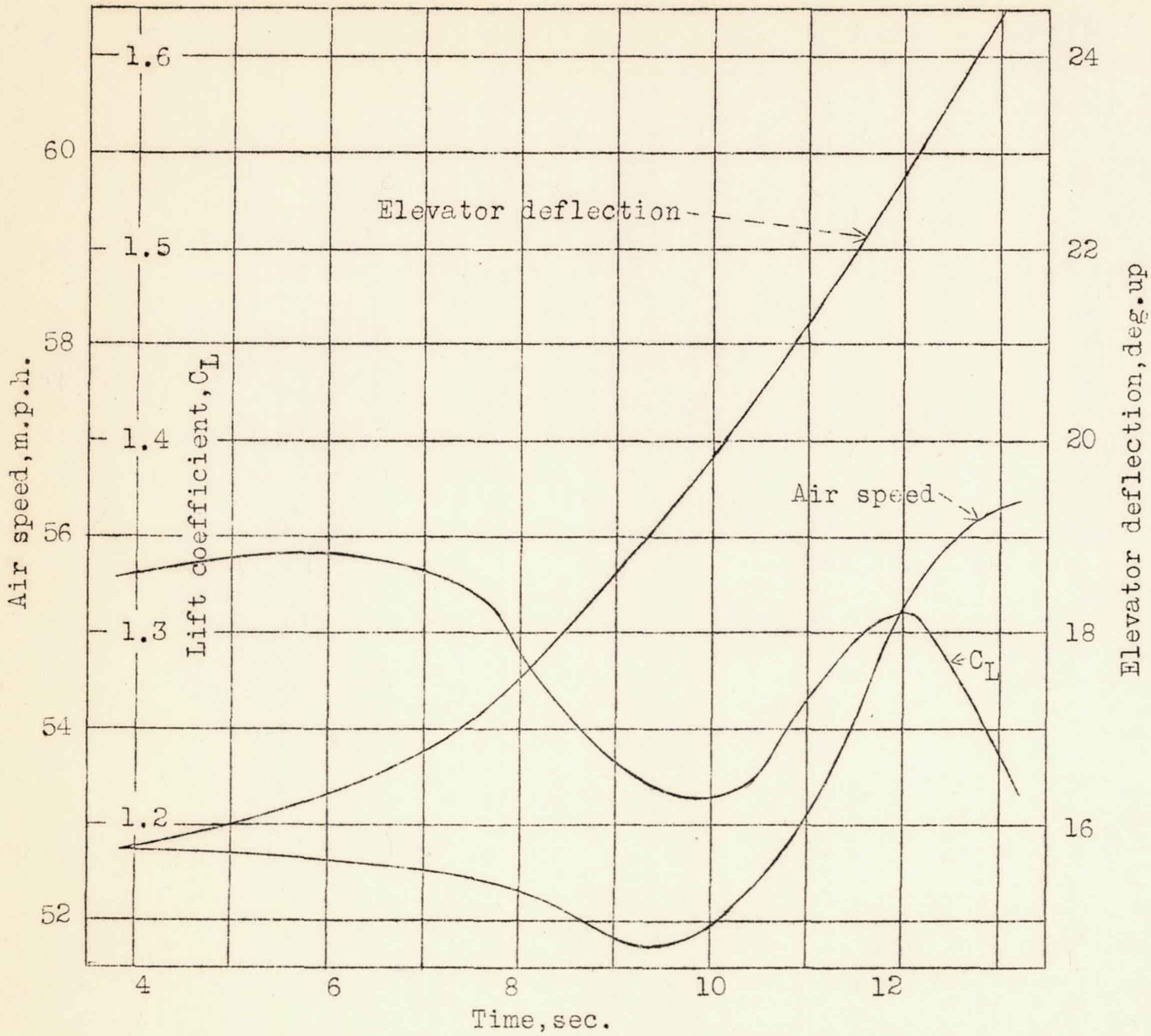

Figure 3.- Time history of instrument records.

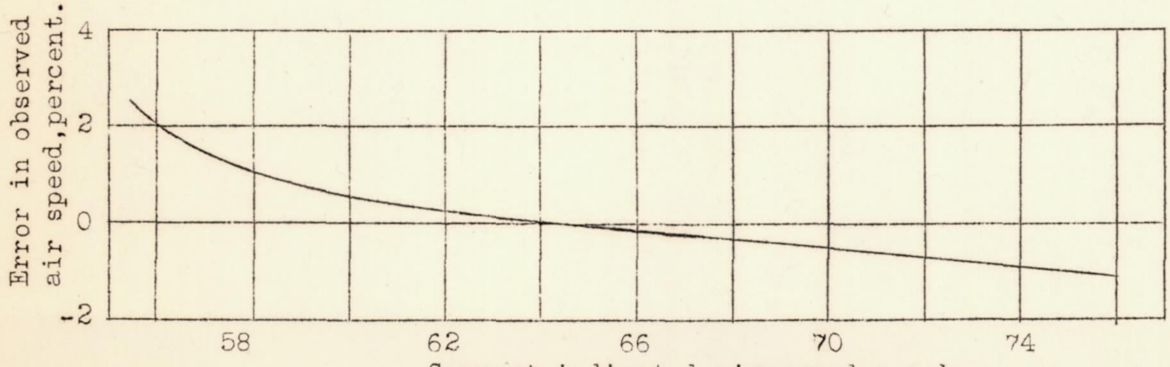

Figure 4.- Calibration of air-speed installation.